Parameterization of Air-Sea Fluxes for High Wind Conditions

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LONG-TERM GOALS

Improved understanding of fundamental processes of turbulence and air-sea interactions.

OBJECTIVES

The standard model for dealing with turbulence and air-sea interactions has three components:

(1) The ocean surface can be characterized by its temperature and aerodynamic roughness.

(2) Given (1) we can use the wind speed and air temperature/humidity to determine the air sea fluxes. All relevant properties of the profiles of the mean and turbulent fields in the surface layer can them be computed with scaling parameters derived from these fluxes using Monin Obukhov Similarity (MOS) theory.

(3) The small-scale properties of the turbulence (structure functions and inertial subrange spectra) can be described solely in terms of the wavenumber/spatial separation and the dissipation rate and these are scaled by MOS.

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Our objective is to investigate various physical processes that lead either to improvements in the representation of the standard model or to violations of the standard model and to develop new models that more thoroughly describe turbulent processes in the marine surface layer. For example, (1) is violated by sea spray, oceanic near-surface mixing processes, and interactions of the wind/stress vectors with the 2-dimensional ocean surface wave spectrum; (2) is violated by near the surface by interactions with waves and is violated far from the surface by intermittent processes associated with larger scale boundary layer dynamics and coherent structures.

APPROACH

In this project we focus on two aspects of the problem that are ripe for significant advancement with existing data and model resources: (1) parameterization of the effects of sea spray, and (2) examination of the parameterization of surface roughness lengths with wind speed for winds greater than 10 m/s These issues are primarily relevant to improving parameterizations in high wind speeds. The field programs of the 80's and 90's have greatly reduced the uncertainty of the representation of fluxes at low and moderate wind speeds and that these results are slowly finding their way into operational weather forecast and climate/GCM models. For example, a recent study found that two operational (ECMWF and NCEP) and two community climate models (CCM3 and GEOS DAS) have flux parameterizations that agree fairly closely for low and moderate wind speeds but begin to diverge wildly for wind speed greater than 10 m/s.

A specification of roughness length, z_o, is required to relate wind speed to surface stress. This may be

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done indirectly by parameterizing drag coefficient in terms of wind speed or by using a Charnock relationship which describes the average drag effect of the spectrum of surface gravity waves

~z_o~=~∀u_*^2/g`+`0.11 nu /u_*

where ∀ is Charnock's parameter, < the kinematic viscosity of air, u_* the friction velocity, and the second term accounts for the transition to smooth flow at low wind speeds. The literature on this subject offers experimental values of ∀ ranging from 0.01 to 0.035 Scalar fluxes (sensible and latent heat) are represented through parameterizations of the scalar roughness lengths (z_{ot} and z_{oq}). The COARE 2.5 algorithm uses a Charnock parameter of 0.011 which agrees well with several recent sets of ETL open ocean measurements for wind speeds less than 10 m/s. However, we have found ∀ begins to increase as wind speed exceeds 10 m/s. Note that ∀ affects both momentum and scalar (heat and moisture) transfer coefficients. Verification of this increase with direct covariance measurements is critical to extending the COARE algorithm to wind speeds greater than 10 m/s. At this writing, the ETL measurements in the FASTEX (Persson et al. 1997) field program in the N. Atlantic in the winter of 1997 are the only source of direct open ocean measurements at these wind speeds. Numerous attempts have been made to relate ∀ to some simple characterization of the surface wave field (e.g., wave age) but so far these have generally been failures. Resolution of this issue requires new measurements and theoretical developments relating turbulence and waves through pressure correlations (their principal mode of interaction)

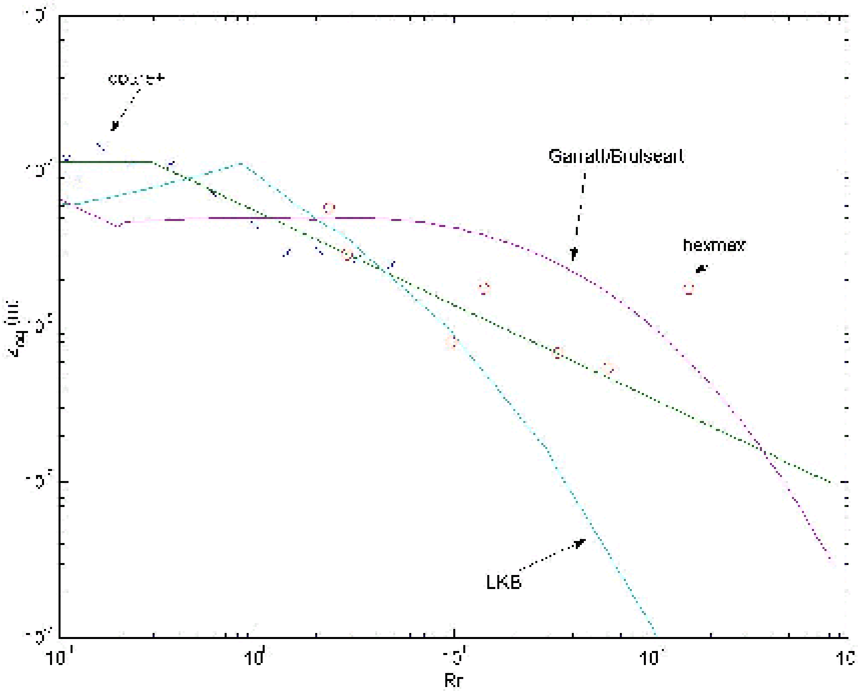
The two major issues that must be resolved to develop a simple but accurate parameterization of sea spray effects are: (1) a characterization of the oceanic droplet source strength as a function of wind speed (i.e., how many droplets of each size are produced by the various sea spray mechanisms and the characteristic height of their introduction) and (2) a characterization of the *feedback effects* in reducing the total droplet contribution. The first issue can only be resolved by direct measurements of droplet spectra and evaporation rates over the open ocean; the second can be attacked with a suitable numerical model. We are aware of only one field program with simultaneous measurements of meteorology and atmospheric concentrations of large droplets at wind speeds above 20 m/s: the 1987 HEXOS program (de Leeuw 1990). Because these are only measurements of droplet concentrations (instead of droplet *fluxes*), an evaporation/turbulent transport model is required to deduce the surface droplet source strength. Thus, a model is required for both aspects of the sea spray problem.

At this writing only the model of Kepert et al. (1999) is sufficiently comprehensive to investigate evaporation/droplet feedback effects in a physically realistic fashion. This model has an upper boundary at 3 km and uses a full order 1.5, level 2.25 closure scheme for MBL turbulence. If we picture sea spray droplets being continuously thrown into the atmospheric surface layer, then their thermodynamic effect is a battle between their evaporation rate and their atmospheric suspension lifetime (i.e., how much water vapor do they transfer to the air before re-impacting the ocean). The full evaporation of droplets is controlled by the sources of heat available to power the evaporation process and interactions between droplets of different sizes. In dynamic equilibrium, there are only three sources: (1) upward turbulent transfer by sensible heat from the ocean, (2) dissipation of turbulent kinetic energy within the MBL, and (3) downward turbulent transfer of heat from the MBL above the droplet layer. Because evaporation of droplets cools and moistens the MBL and the surface layer, these heat sources adjust internally until some equilibrium is approached. This feedback limits the amount of evaporation produced regardless of the numbers of droplets ejected by the ocean. Thus, this problem cannot be investigated without realistic incorporation of full MBL-scale physics.

WORK COMPLETED AND RESULTS

In the previous year we concentrated on processing the flux data from the FASTEX experiment and associated improvements in the COARE bulk flux model, including a new representation of the Charnock parameter. In the last year we have worked on completing and publishing version 2.6 of the COARE flux algorithm. The majority of the effort involved reanalysis of four ETL flux data sets and results from the 1987 HEXMAX experiment in the North Sea. The LKB scalar roughness relationship used in COARE 2.5 has been replaced with a much simpler one that fits both the COARE and HEXMAX data bases.

Two figures are shown below to summarize the latest flux analysis and indicate comparisons with the bulk algorithm. The upper panel shows direct, open ocean measurements of moisture roughness length as a function of the roughness Reynolds number ($Rr=z_o u_*/<$): x's are the ETL data sets (Met4) and o's are reprocessed HEXMAX data. The blue line labeled LKB is the original COARE 2.5 representation; the green line is the new COARE 2.6 model. While the Met4 and HEXMAX data differ substantially when plotted as transfer coefficient vs wind speed, they agree well when plotted as roughness length vs Rr. Using this new fit, we have extended the COARE flux algorithm to Rr of about 200, which is equivalent to an open ocean wind speed of about 22 m/s (the previous version was considered to be verified to 10 m/s). The lower hand panel shows a comparison of direct measurement with bulk



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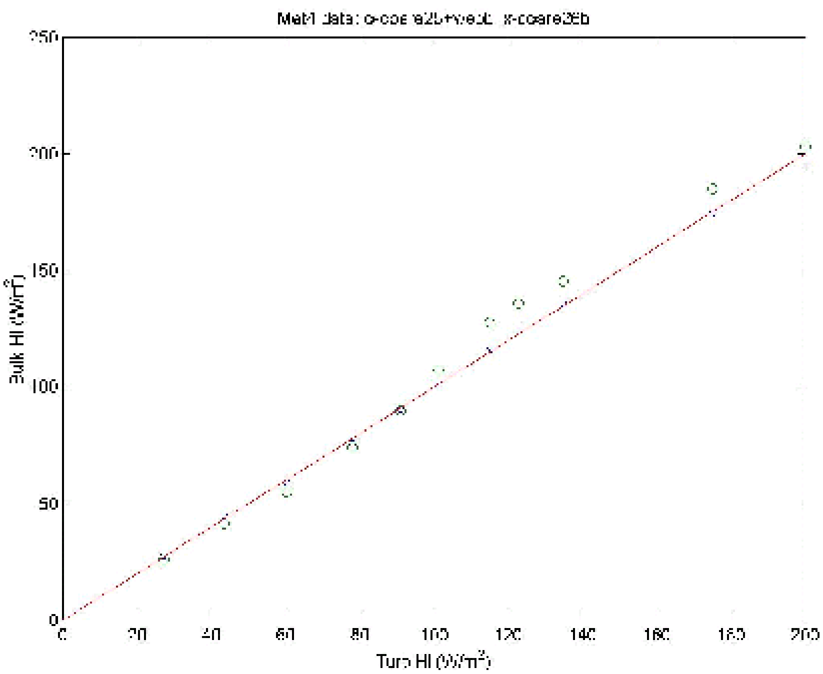

estimates of the latent heat flux for the 1405 hourly values (wind speeds from 0-12 m/s) from the Met4 data set; the circles are version 2.5 and the x's are version 2.6. The new scalar roughness parameterization removes the 'dip and hump' present in version 2.5 (but not in the data) at intermediate winds speeds and extends the model for direct (i.e., non-droplet mitigated) transfer from 12 to 22 m/s.

The KF model (Kepert et al. 1999) has been used to investigate various aspects of boundary-layer interaction under the influence of sea spray and to aid the development of a simple droplet parameterization suitable for use in numerical forecast models. As part of this effort, a new droplet evaporation parameterization was developed that accounts for feedback effects This parameterization has been used in coupled air-sea simulation of hurricane Opal; significant droplet effects were found (Bao et al. 2000). It has become clear that a major issue for droplet effects on tropical cyclone strength is the net sensible heat transferred to the atmosphere by droplets which re-impact the ocean without substantial evaporation. The model is now well-developed; major progress on this topic awaits new measurements of droplet concentrations at wind speeds greater than 20 m/s.

IMPACT/APPLICATIONS

The bulk flux routine incorporates many innovations (gustiness, cool skin and warm layer effects, proper convective functions, rain heat and momentum flux, Webb effect, and a saturation Richardson number in unstable conventions); it is expected to become a community standard and should be incorporated into operational weather forecast models (e.g., the Navy's). The work done on sea spray is expected to improve forecasts of strong storms Working jointly with Jim Edson, experimental techniques to measure fluxes from ships were advanced considerably over the last 4 years. The systems developed will greatly improve air-sea flux information in future field programs.

TRANSITIONS

As discussed above, the new bulk algorithm and bulk Richardson number parameterization could be adopted in Navy operational forecast models. Our new flux measuring techniques have been applied to the gas exchange problem.

RELATED PROJECTS

"Toward a definitive determination of air-sea gas exchange", NOAA Climate and Global Change Program. This is an investigation of fluxes and flux parameterization methods for trace gases (e.g., carbon dioxide) exchange processes over the ocean.

"Shipboard measurements of cloud-radiative properties in the tropical western Pacific", Department of Energy ARM program, (DE-AI02-92ER61366). This is a study of cloud forcing of the oceanic surface energy budget.

"Environmental sensing", DoD Advance Sensor Application Program (P.ETL.2090). Investigation of air-sea interaction aspects of remote sensing of the sea surface.

“Mid-Oceanic Wintertime Surface Fluxes and Atmospheric Boundary Layer Structure: Relationship to Cyclone Development and Evolution”, NSF. O. Persson, P.I.

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